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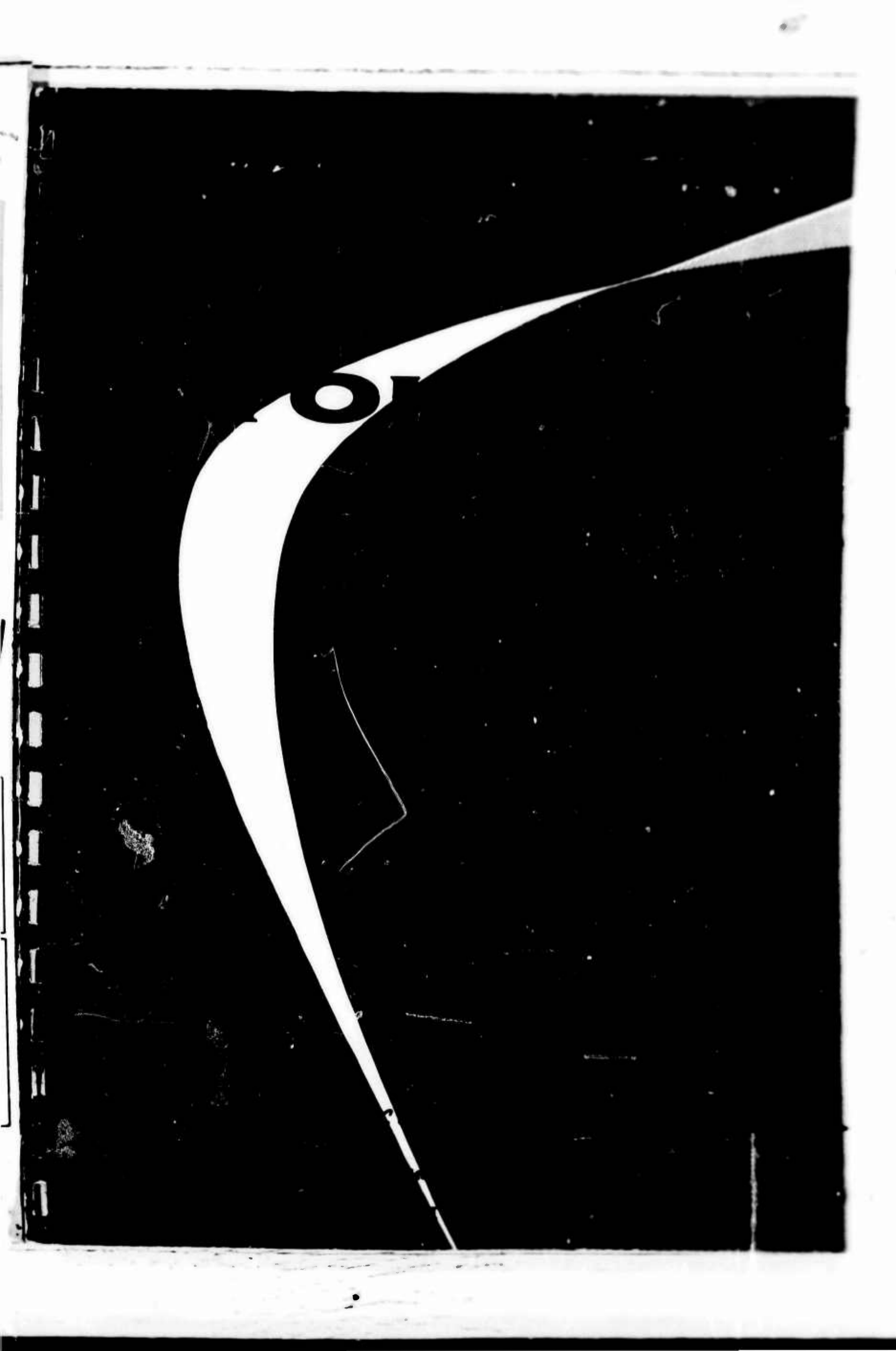
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Comparative Study of Various Types of **VTOL Transport Aircraft**

DUCTED FAN DESIGN STUDY OF THE VERTODYNE REPORT R-80

Vertol Aircraft Corporation Morton, Pennsylvania



Research and Development Program

Contract NONR 1681(00)

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I. SUMMARY

The fluid flow principles of ducted fan propulsion are reviewed and developed for several duct configurations. Momentum theory has been modified by duct pressure loss concepts to provide an understanding between duct and fan requirements. The thrust per horsepower capabilities are shown to be a function of duct shape and the fan design is incidental to such propulsion efficiency; however, for a given duct a specific fan is defined and required.

For the vertodyne transport configuration of Ref. (1) the thrust per horsepower requirements, fan sizes and required blade design parameters were determined. A perfect bellmouth entry with no downstream diffusion has been assumed as the basis of the fan design.

Thrust control by variable guide vanes has been evaluated and satisfactory thrust reductions have been obtained at inlet vane turning angles between 0 and 20°. Further basic cascade test data is required to evaluate the ability to obtain such inlet vane turning angles.

II. SYMBOLS

A	Area, ft^2
D	Diameter, ft
M	Mass, slugs
m	Annulus ratio, R_R/R_T
N	Number of blades
n	Rotational speed, RPM
P	Pressure, lb/ft^2
Q	Volume flow, ft^3/sec
R	Radius, ft
T	Thrust, lbs
V	Velocity, fps
W	Resultant velocity, cascade inlet, fps
w	Disc Loading, lb/ft^2
ω	Rotational velocity, radians/sec
ρ	Mass density, slugs/ ft^3
σ	Density ratio, ρ/ρ_0 ; or cascade solidity
β_1	Inlet angle, cascade
β_2	Exit angle, cascade
θ	Turning angle, cascade
α	Cascade angle of attack
ϕ	Cascade angle of incidence
Z	Inlet vane turning angle

Subscripts:

A	Axial
E	Exit
F	Fan (or propeller)
I	Inlet
R	Root
T	Tip
U	Tangential component, cascade flow
∞	Infinity

III. INTRODUCTION

The objective of this report was to present the operating principles of free and ducted propellers and then to specifically evaluate the ducted propeller requirements for the Vertodyne. The words "fan" and "propeller" are considered synonymous in this report. This entire study has been limited to static thrust conditions, but could, of course, be extended to encompass various inflow ratios.

This design study was preceded by a review of all the available literature on the subject of ducted fans and propellers. Various agencies and personnel were contacted including the Langley Aeronautical Lab, the University of Wichita and Professor H. B. Helmbold, now of Fairchild Aircraft Corporation, Hagerstown, Maryland. In addition, the principles developed and used by VERTOL in the design of aircraft cooling fans were employed where suitable.

Momentum principles have been used to analyze the flow through ducted propellers and it has been shown that for a given diameter the thrust per horsepower of a propulsion unit consisting of a duct through which a fluid is pumped can be greater than a free propeller.

It has also been shown that the duct defines the thrust per horsepower capabilities and the fan or propeller is an accessory to the propulsion unit; the propeller is a necessary evil but need not be considered when comparing thrust per horsepower capabilities of various duct configurations (or "free" propellers).

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There is a limit, however, to the neglect of the propeller--that is the efficiency of the propeller. In general, a ducted propeller will be more efficient than a free propeller due to the reduction in tip losses. This means that flow comparisons made on the basis of equally efficient propeller discs either in a ducted or free system will be conservative for the ducted propeller.

Various duct designs are possible ranging from one which would enclose the stream tube of a free propeller to an expanding nozzle type. The difference in such duct designs is the ratio of the area at exit compared with that at the propeller. Momentum principles reveal that the greater the ratio of A_E/A_F , the greater the value of T/HP can be.

Considerable emphasis has been placed on the design requirements of the duct. The duct has been considered as a flow pressure loss (or increase at the fan disc) system. Inlet losses, for instance, severely detract from the T/HP capabilities of a ducted propulsion system. In addition, neglecting the propeller in this case can be quite optimistic since flow disturbed by the entry can reduce the propeller efficiency.

Diffusion ratio, A_E/A_F , also has limitations imposed by separation in the diffuser. If a gradual expansion of 7° cannot be maintained, some form of induced or forced control of separation is indicated.

The duct design chosen for specific analysis for the Vertodyne has been selected as a non-diffusion duct with a perfect bellmouth entry. Mass flow requirements were determined and the fan pressure rise and vector diagrams were thus defined. The required fan was then designed on the basis of NACA cascade data, reference 4.

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Thrust control was proposed by inlet guide vanes. The analysis shows that the thrust can be effectively reduced at inlet vane turning angles between 0 and 20 degrees. However, no cascade test data is available for the existing inlet vane cascade situation of $\beta_i = 0^\circ$. Such basic test data is one of the recommended programs necessary for ducted fan propulsion units.

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IV. DUCTED FAN CONCEPT

A discussion of ducted fan application to propulsion or vertical lift may best be begun by reviewing the momentum principles of a non-ducted or "free" propeller. The discussion will be limited to static thrust conditions.

The thrust of an ideal free propeller may be expressed as

$$T = M \Delta V \quad (1)$$

However, since there is no other body for the thrust to act upon except the propeller, thrust may also be written as

$$T = A_F \Delta P_F \quad (2)$$

Equating 1 and 2

$$P_F = \frac{M \Delta V}{A_F} = \frac{\rho (A_F V_F)(V_\infty - V_0)}{A_F} \quad (3)$$

The fan pressure rise may also be expressed simply as the required velocity head developed, or

$$P_F = \frac{1}{2} \rho V_\infty^2 \quad (4)$$

Equations 3 and 4 may now be solved for the well known relationship between V_{fan} and V_∞

$$\frac{\rho A_F V_F V_\infty}{A_F} = \frac{1}{2} \rho V_\infty^2 \quad (5)$$

$$V_F = \frac{1}{2} V_\infty$$

The ideal fan power is

$$P = Q \Delta P = A_\infty V_\infty \frac{1}{2} \rho V_\infty^2 = \frac{1}{2} \rho A_\infty V_\infty^3$$

and the thrust is

$$T = M \Delta V = \rho A_\infty V_\infty^2 \quad (6)$$

The principle that Thrust is a function of V_e^2 and Power of V_e^3 is apparent; by increasing mass flow and decreasing V_e , the basic "improvement" in T/HP referred to in ducted fan propulsion is obtained.

The following specific equations may be developed:

For constant disc loading

$$\frac{T/HP_{DUCTED}}{T/HP_{FREE}} = \sqrt{2 \frac{A_E}{A_F}} \quad (7)$$

For constant power and disc area

$$\frac{T/HP_{DUCTED}}{T/HP_{FREE}} = \sqrt[3]{2 \frac{A_E}{A_F}} \quad (8)$$

Thrust per horsepower capabilities of propellers based on the above momentum considerations are presented on Figure 1. The area of helicopter and aircraft propeller operation are noted and one set of available ducted propeller (reference 6) test data* is shown. To incorporate such data conveniently, Figure 1 is at standard sea level conditions.

*The included ducted propeller tests are based on reference 6 by Robert J. Platt, Jr. Discussions with Mr. Platt have indicated that the propeller-duct combination was not necessarily operated on design.

V. DUCT DESIGN AND LIMITATIONS

That an improvement in T/HP can be obtained by shrouding a propeller of a given diameter and thus controlling the downstream flow contraction is well known, but it can be shown that an improvement can be obtained only by use of the correct duct shape; improper ducting can decrease T/HP compared with an equal diameter "free" propeller.

It therefore becomes apparent that the duct design is the basic issue and for a specific duct a fan is then defined. It should be mentioned here that it is too much to expect that a given fan can be evaluated as being "better" or "worse" in or out of a shroud; the fan must be designed for ^{one} installation and could be completely off design for the other.

Such thinking leads to the obvious requirement of an understanding of the inter-relationship between duct and fan. This may be most easily visualized by considering the problem as a duct-flow pressure loss problem. Figure 2a, b, c and d pictorially present the traces of total, static, and velocity pressure which would occur through several duct configurations (including a classical "free propeller"). It can be seen that the pressure rise required through the fan is equal to the downstream velocity pressure plus, as in Figure 2d, any other penalties such as friction or entry losses.

To show the seriousness of such additional duct losses, Figure 3 presents thrust/horsepower for a fan of the Vertodyne configuration size. With a perfect bellmouth entry the expected gain in T/HP with increasing diffusion ratios is apparent and at a diffusion ratio of 2:1 can double

the T/HP of a "free propeller" of equal diameter and efficiency. Actually, Figure 3 has been based on fan efficiencies of nominally 100%. Since a ducted fan of such an R_R/R_T can be expected to be 90% efficient while a free propeller may be more nearly 80% efficient, an increase of more than twice the T/HP of an equal diameter free propeller may be determined in testing. It must be remembered that to provide a diffusion ratio of 2:1 either (1) a long diffuser of about 70° included angle must be provided, or (2) separation must be prevented by induced or forced circulation (boundary layer control). The power requirements to the aircraft (such as turbine bleed) of any boundary layer control system would need to be evaluated against expected diffusion gains.

However, Figure 3 also presents the variation of T/HP for ducts having varying degrees of entry losses. With a loss of only $.25q$ the duct is hardly better as a lifting or propelling device than a free propeller of equal diameter. With an entry loss of $.5q$ (which is representative of a sharp edged hole in a flush surface such as a wing) the T/HP is less than a free propeller and actually gets worse as mass flows are increased by providing greater diffusion ratios. The use of a simple tube entry where $\Delta P/q$ approaches 1.0 can provide only $1/3$ the thrust for a given horsepower than a free propeller of equal diameter! Even worse, such entry losses can provide disturbed flow to the fan and further decrease T/HP due to loss in fan efficiency.

Figures 4 and 5 present the thrust per horsepower requirements of the Vertodyne if the fan area can be increased. The obvious advantage of increased fan area is readily apparent and simply reiterates the basic

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principle of the advantages of lower disc loading. Figure 6 has been cross plotted from the above data specifically for a 1:1 diffusion ratio duct. At zero entry loss conditions thrust per horsepower can be increased 40% if the fan annular area can be doubled.

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VI. FAN DESIGNA. Design Basis

In order to present the fan design requirements for the Vertodyne transport (reference 1), the following assumptions were made:

1. Duct entry will be an ideal bellmouth. No flow energy losses.
2. Diffusion will be accomplished with no separation.
3. Available cascade data (references 3 and 4) may be extrapolated where necessary, although design will be held within the range of available cascade data where possible.

The design conditions are:

Altitude	6000'
Ambient Temp.	95°F
Gross Weight	112,000 Lbs. (approximately)

B. Fluid Flow Requirements

Mass flow requirements were determined for various exit areas and the fan pressure rise was determined from

$$\begin{aligned}\Delta P_F &= \Delta P_{\text{ENTRY}} + \Delta P_{\text{FRICTION}} + \Delta P_{\text{DIFFUSION}} + \Delta P_{\text{EXIT}} \\ &= 0 + 0 + 0 + \frac{1}{2} \rho V_E^2\end{aligned}$$

The fan flow parameters are plotted on Figures 7 and 8.

C. Fan Configuration and Inlet Geometry

Two fan speeds were arbitrarily selected:

$$W_1 = 800 \text{ fps}$$

$$W_2 = 900 \text{ fps}$$

This was done to preclude the possibility of sudden drag divergence at high subsonic Mach numbers. The fan was considered to consist of an inlet stator (or guide vanes), rotor, and exit stator. The inlet guide vanes were set at zero for the design condition, but were considered in Section V-E of this report as the thrust controlling mechanism. The fan inlet angles, required turning angles and required powers were then determined for various ratios of m ($m = R_{\text{root}}/R_{\text{tip}}$). These data are plotted on Figures 9 to 14 for three different divergence ratios, $A_E/A_F = 1.0, 1.5$ and 2.0 . The limiting value where the root inlet angle β_{iR} equals the required turning angle has been determined from Figures 9 to 14 and as such has defined the minimum R_R/R_T ; this provides the greatest fan annulus over which constant pressure blade design can be provided.*

The resultant values of $\beta_{i \text{ root}}$, $\beta_{i \text{ tip}}$, Θ_{root} , Θ_{tip} , V_{axial} , RPM, Power, and m have all been plotted for the minimum value of m vs diffusion ratio on Figures 15 and 16.

No fan efficiency has been included in the required power, "air" horsepower only is shown, but the effect of decreasing annulus and diffusion ratio is apparent in Figure 17. Substantial gains in T/HP are apparent with increasing diffusion ratio, but the effect of annulus area rapidly diminishes below R_R/R_T of about 0.3.

*Constant pressure blading was recommended in discussion with NACA personnel at Langley Aeronautical Laboratory in view of downstream mixing losses. Testing may indicate a larger gain due to increased annulus than losses due to downstream mixing but at the current state of the art constant pressure blading appears to be a logical first estimate.

D. Fan Blading

The first practical application of ducted fans for static, vertical lift might well be based on a diffusion ratio of 1.0 (inlet area = fan area = exit area). This may be done to preclude the variables of diffusion separation control and has been considered for the continuance of this study.

For $A_E/A_F = 1.0$ the required fan blading has been determined from references 4 and 5. These data are presented in Table I.

E. Inlet Guide Vane Control

Two possibilities of fan thrust control are (1) collective pitch control of the rotor blades and (2) inlet guide vane control. Inlet guide vanes have been considered in this study due to the inherent mechanical simplicity of such control compared with collective pitch.

The inlet vanes have been assumed capable of turning the flow by various amounts and the resulting pressure rise through the vanes, rotor and stator have been calculated. A balance of fan ΔP and exit velocity pressure define the thrust output. Decreased thrust only has been considered, the fan having been designed for a maximum static thrust of 112,000 pounds.

It should be noted that the inlet vane incidence angles required to produce the required inlet flow turning angles was not determined. Test data for cascades at inlet angles approaching 0° will be required to estimate the inlet vane incidence angles. The maximum turning angle (2) required to reduce total thrust from 112,000 lbs. to 84,000 lbs. is 16° . This would seem to be a reasonable value. Inlet vane turning angle is presented vs thrust on Figure 18.

VII. RESULTS AND CONCLUSIONS

An aircraft with two ducted fans located in the wings has been studied to evaluate the type of fan and duct required to provide a hovering ability at 6000' pressure altitude, 95°F ambient temperature. The following specific conclusions may be listed:

1. For the disc loading of the 112,000 pound Vertodyne transport with 16.7' fans a properly ducted fan can provide a Thrust to Horsepower ratio as great as 3.8.
2. Details of a ducted fan installation intended to provide vertical lift are as follows:
 - a. Momentum theory appears applicable when modified by the flow pressure loss considerations of the duct.
 - b. Inlet design requires a "perfect bellmouth". Severe decrease in T/HP results when inlet pressure losses are encountered. For the subject aircraft, an inlet loss of $\Delta P/q = .25$ results in a ducted fan of essentially no greater T/HP than a free propeller of the same diameter.
 - c. If fan disc loading can be decreased, a substantial increase in T/HP can be obtained; increasing from a maximum value of 3.8 lb/HP at a disc loading of 292 lb/ft²* to 5.5 lb/HP at a disc loading of 140 lb/ft²**.

The above figures are based on a downstream diffusion ratio of 2:1.

*Subject configuration; G.W. = 112,000 lbs., $A_F = 2(190) = 380 \text{ ft}^2$
**G.W. = 112,000 lbs., $A_F = 2(400) = 800 \text{ ft}^2$

d. If downstream diffusion is limited to 1:1 ($A_{fan} = A_{exit}$), which may be a practical installation, the maximum thrust per horsepower for the subject configuration is 2.7 lb/HP. A decrease in disc loading to 140 lb/ft² can provide an increase in T/HP to a maximum value of 3.9 lb/HP.

e. For a practical 1:1 area ratio duct, the following detail data have been determined for the Vertodyne:

- (1) Thrust per Fan = 56,000# @ 6000' @ 95°F
- (2) Fan Outside Diameter = 16.7 ft
- (3) Fan Inside Diameter = 5.9 ft
- (4) Fan RPM = 919
- (5) Horsepower per Fan = 20,200

f. The thrust per horsepower of this practical 1:1 fan is estimated to be at least 50% greater than a free propeller of equal diameter.

VIII. RECOMMENDATIONS

1. Test programs to evaluate ducted fans should be initiated. A recommended procedure might be:
 - a. Determine flow characteristics and pressure losses of the duct without a fan with duct modifications as required.
 - b. Determine fan efficiencies by testing the fan alone per ASME Standards with fan modifications as required.
 - c. Evaluate the fan in the duct.
2. Extend the range of cascade test data now available. Inlet angles approaching 0° should be evaluated for thin symmetrical airfoils for use in inlet guide vane design.
3. Extend the range of cascade tests to provide inlet angle data lower than 30° for 65 series compressor sections.

IX. REFERENCES

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6. Platt, Robert J. Jr.; "Static Tests of a Shrouded and an Unshrouded Propeller" - NACA RM L7H25 - February 1948

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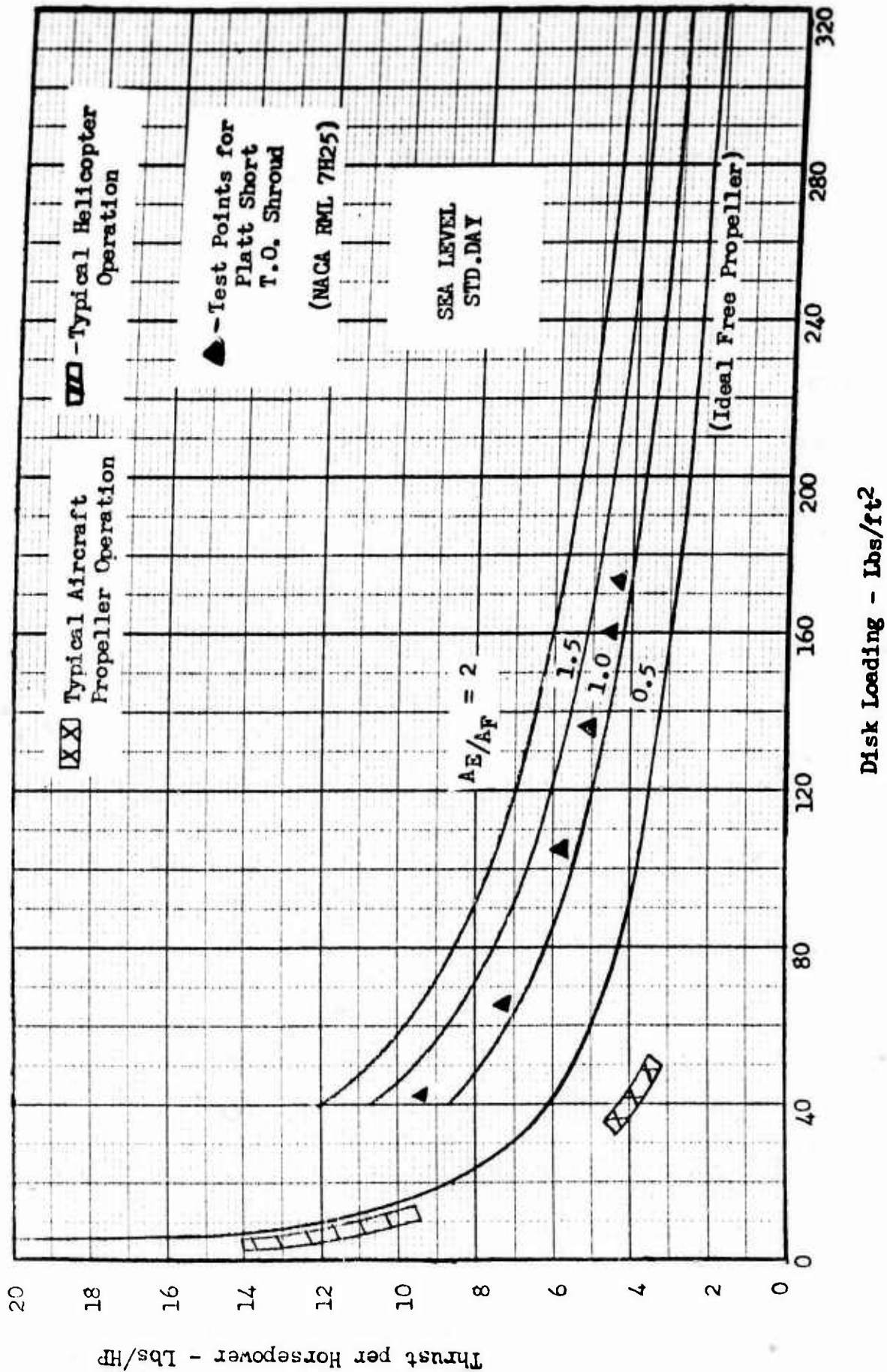
TABLE I

FAN DATA TABULATION
(AE/AF = 1.0) $\rho = 0.00178$ Slugs/Ft³
For Minimum Root Radius

	W _{1t} FAN	=	900 fps STATOR	W _{1t} FAN	=	800 fps STATOR
D _{tip} , ft	16.7		16.7	16.7		16.7
m	0.355		0.355	0.44		0.44
D _{root} , ft	5.92		5.92	7.35		7.35
No. Blades	9.		7.	9.		7.
ω	96.1			81.5		
n - rpm	919.			778.		
TIP:						
Airfoil	65-410		65-(15)10	65-710		65-(17)10
σ	0.5		0.5	0.5		0.5
θ	3.2°		13.95°	5.6°		17.0°
α	4.4°		7.7°	6.5°		10.3°
β	63.3°		13.95°	58.2°		17.0°
ϕ	31.1°		83.7°	38.3°		83.3°
Chord, ft	2.92		3.75	2.92		3.75
ROOT:						
Airfoil	65-(17)10		65-(17)10	65-(17)10		65-(17)10
σ	1.5		1.5	1.5		1.5
θ	35.05°		35.05°	34.9°		35.0°
α	20.1°		19.9°	19.0°		19.9°
β	35.05°		35.05°	35.4°		35.0°
ϕ	75.0°		74.8°	73.6°		74.8°
Chord, ft	3.09		3.98	3.85		4.94

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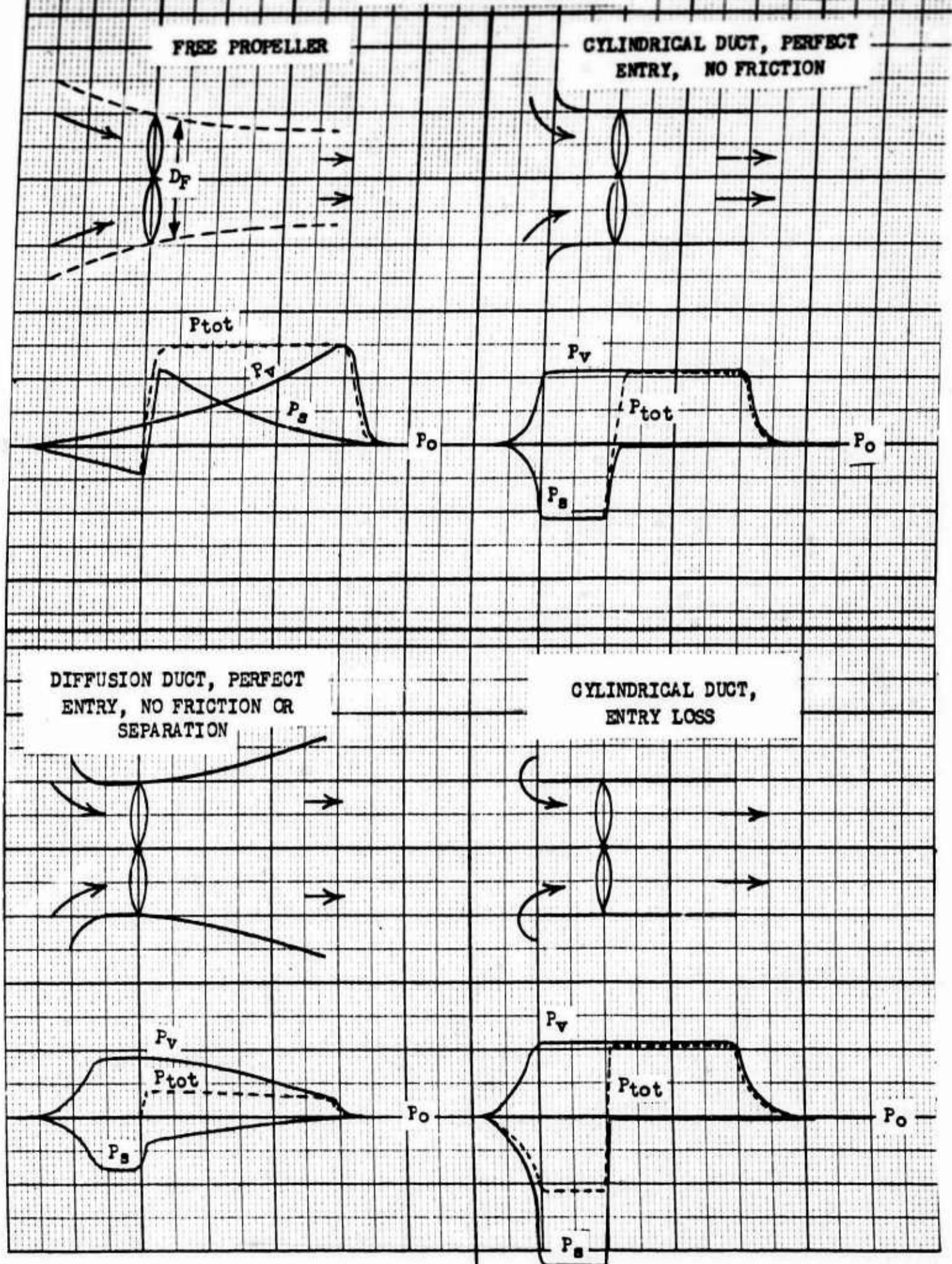
FIGURE 1
STATIC THRUST CHARACTERISTICS OF DUCTED FANS IDEAL
THRUST PER HORSEPOWER VS DISK LOADING SEA LEVEL - STANDARD DAY



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FIGURE 2
FLOW PRESSURE TRACES

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FIGURE 3

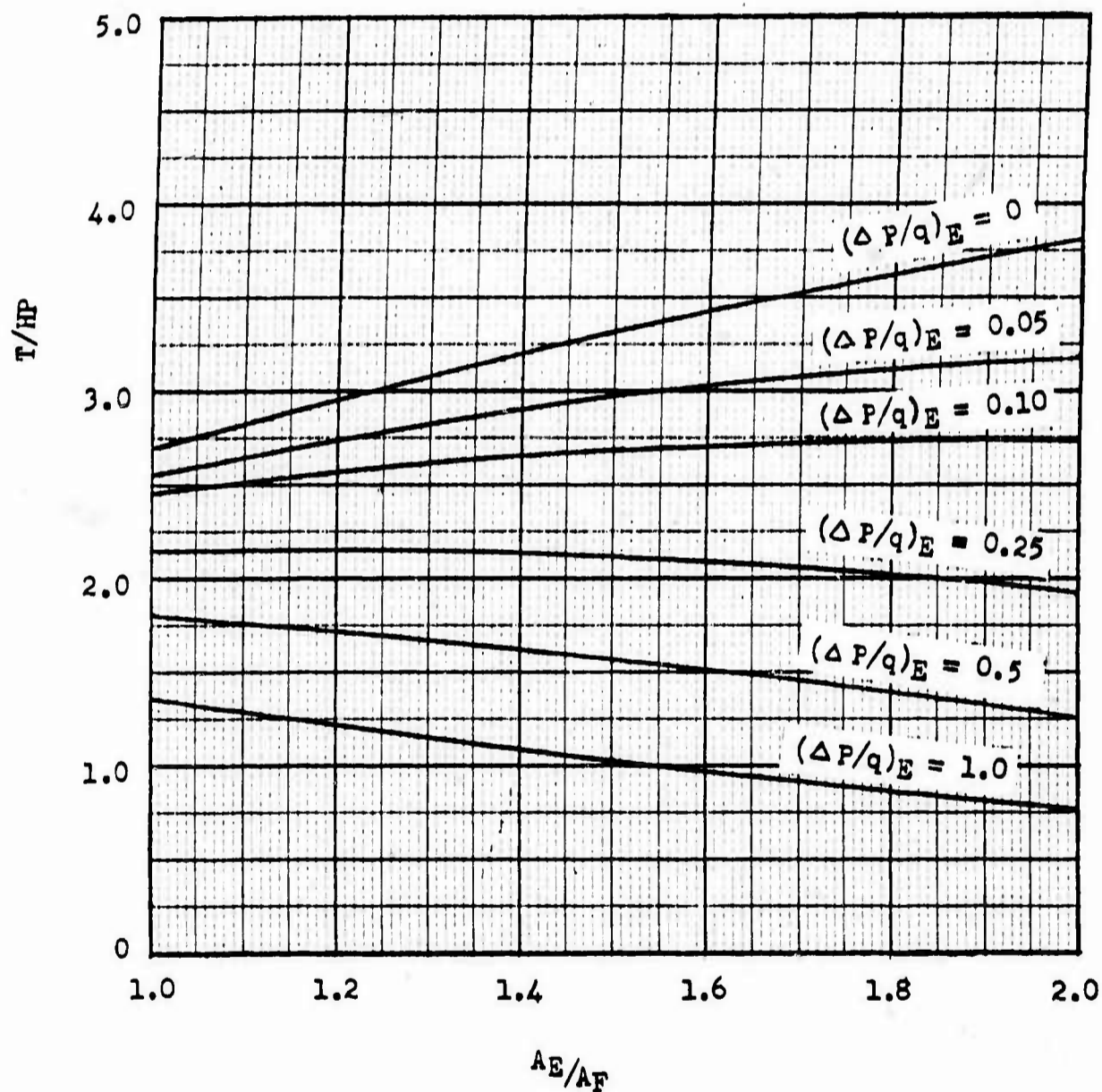
VARIATION IN THRUST PER HORSEPOWER WITH DIFFUSION
RATIO FOR SEVERAL INLET LOSS CONFIGURATIONS

$$T = 56,000\#$$

$$w = 291.7\#/ft^2$$

$$A_F = 192\ ft^2$$

$$\mu = 0.00178\ \text{slugs}/ft^3$$



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FIGURE 4

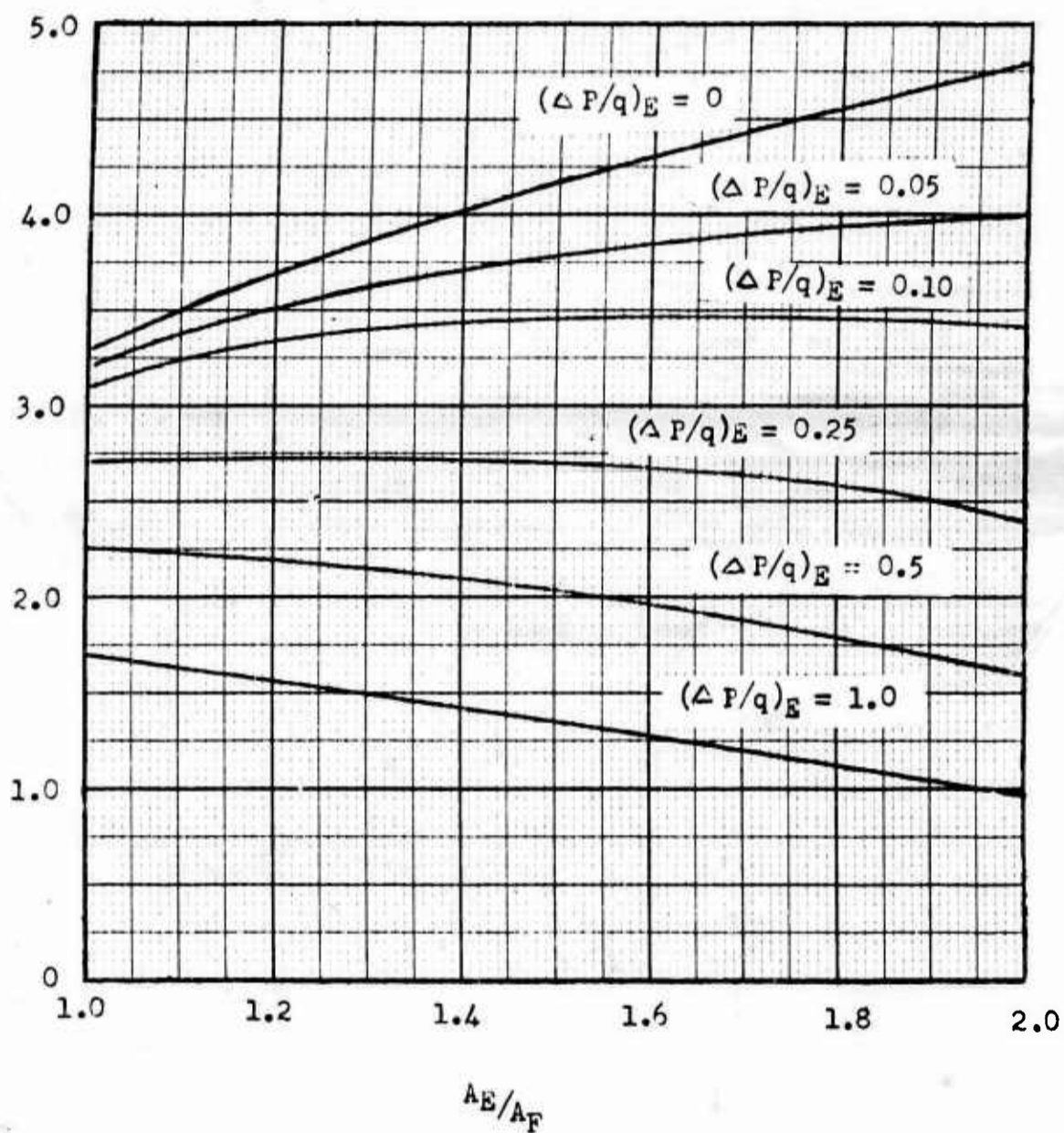
VARIATION IN THRUST PER HORSEPOWER WITH DIFFUSION
RATIO FOR SEVERAL INLET LOSS CONFIGURATIONS

$$T = 56,000\text{#}$$

$$w = 186.6\text{#/ft}^2$$

$$A_F = 300\text{ ft}^2$$

$$\rho = 0.00178\text{ slugs/ft}^3$$



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FIGURE 5

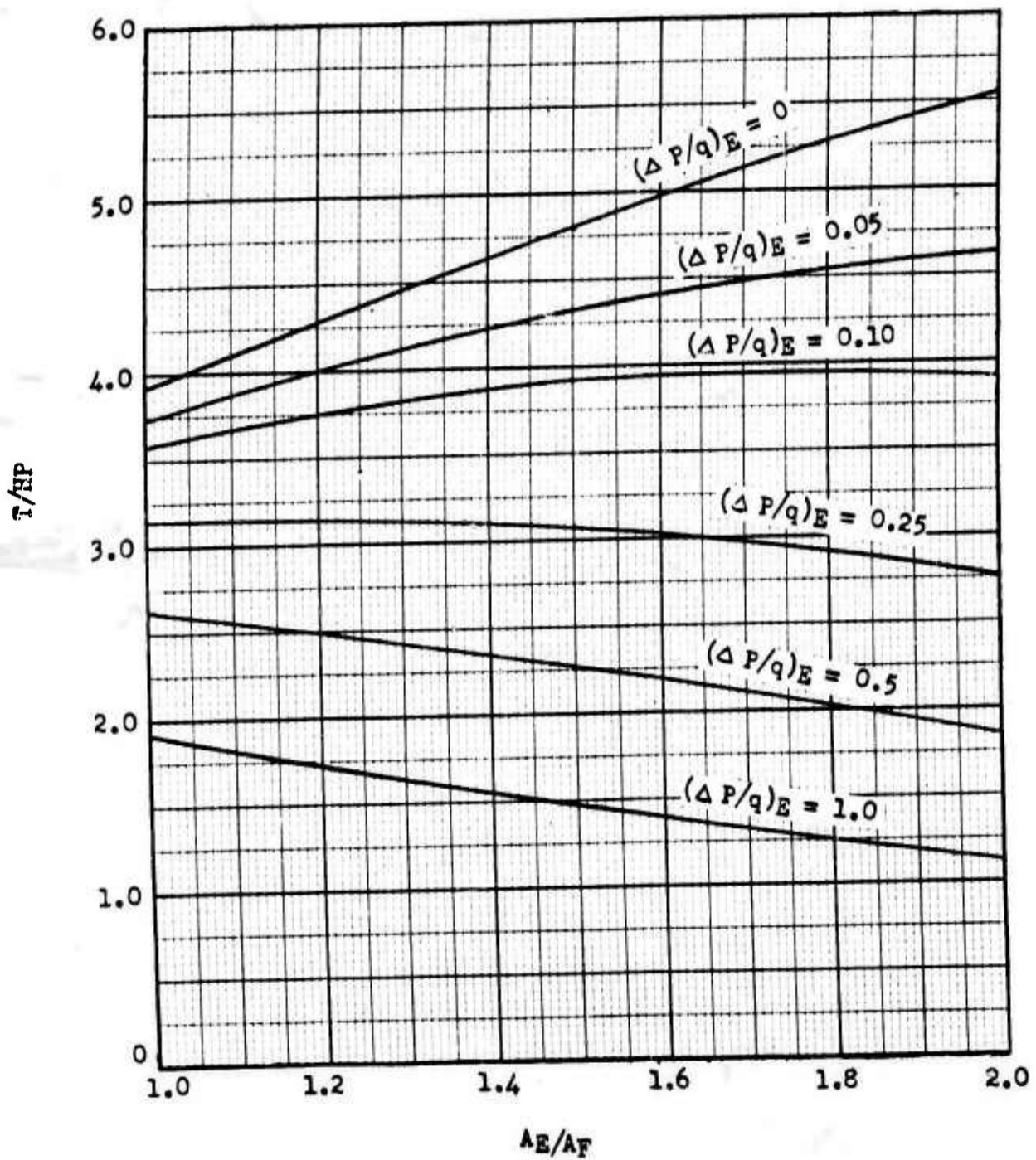
VARIATION IN THRUST PER HORSEPOWER WITH
DIFFUSION RATIO FOR SEVERAL INLET LOSS CONFIGURATIONS

$$T = 56,000\#$$

$$A_F = 400 \text{ ft}^2$$

$$w = 140\#/ft^2$$

$$\rho = 0.00178 \text{ slugs/ft}^3$$



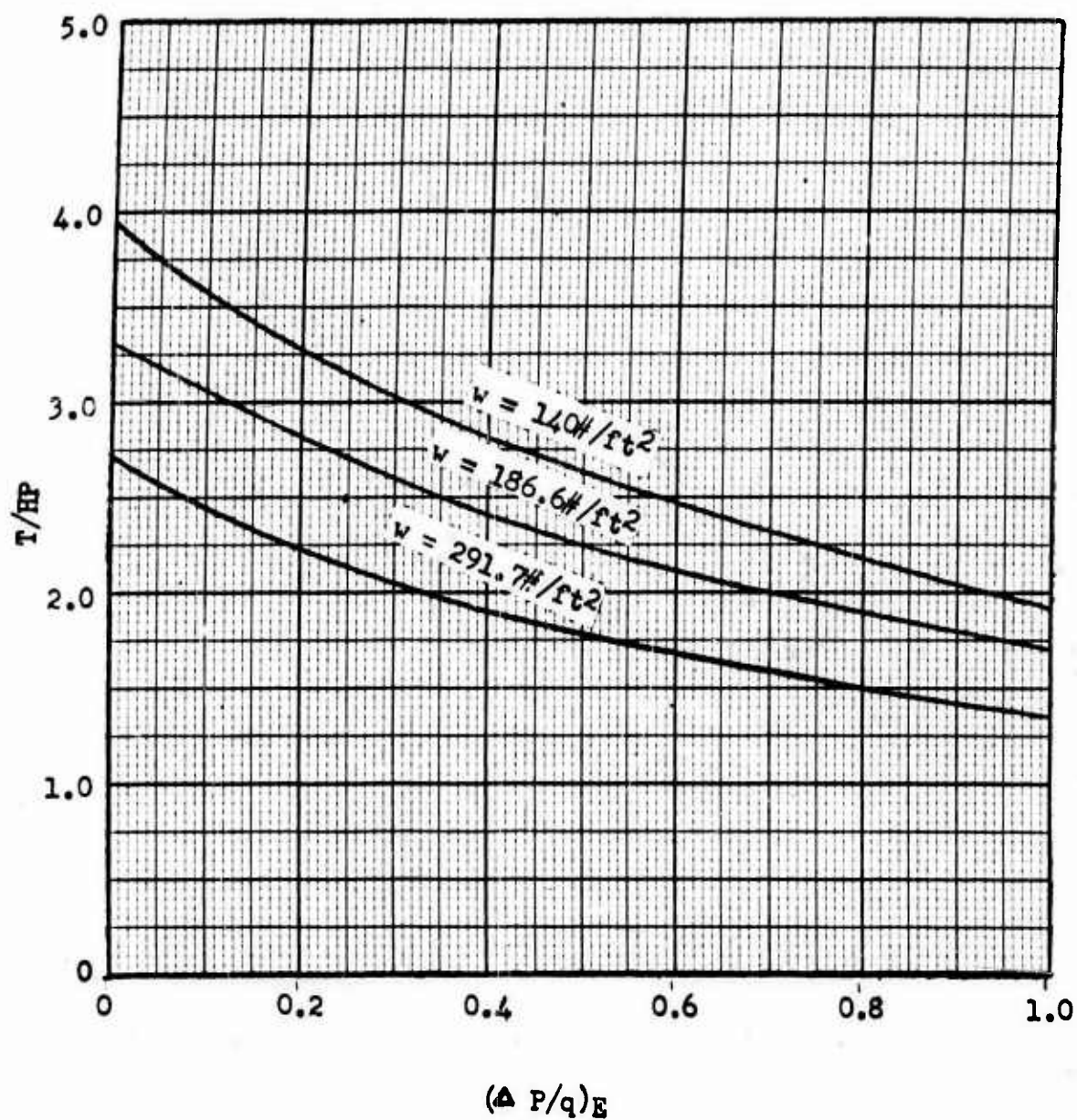
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FIGURE 6
THRUST PER HORSEPOWER VS
INLET PRESSURE LOSS COEFFICIENT

$$T = 56,000\#$$
$$\rho = 0.00178 \text{ slugs/ft}^3$$

$$A_E/A_F = 1.0$$

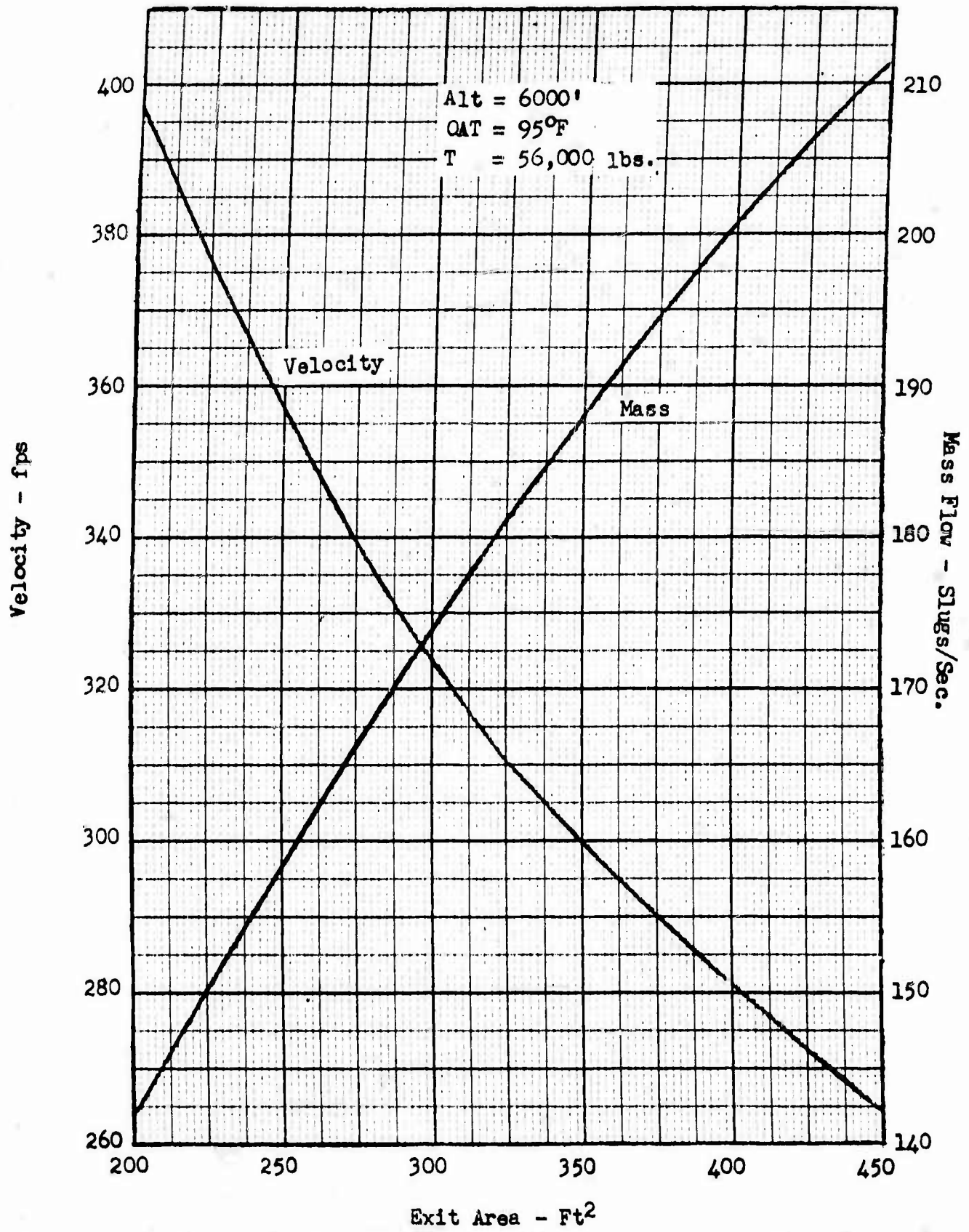


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FIGURE 7
EXIT VELOCITY & MASS
FLOW VS EXIT AREA

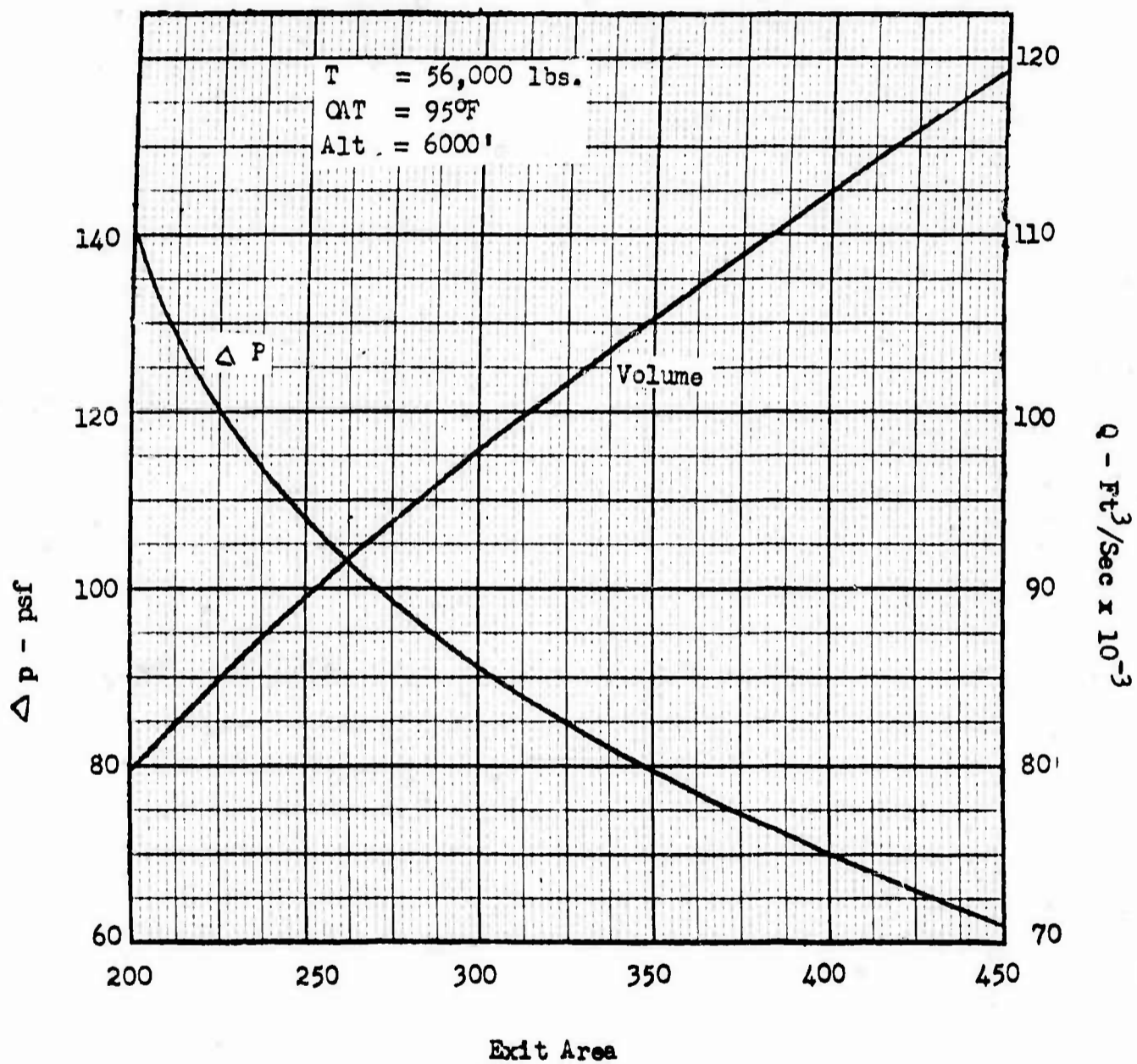


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FIGURE 8
EXIT VELOCITY PRESSURE &
VOLUME FLOW VS EXIT AREA

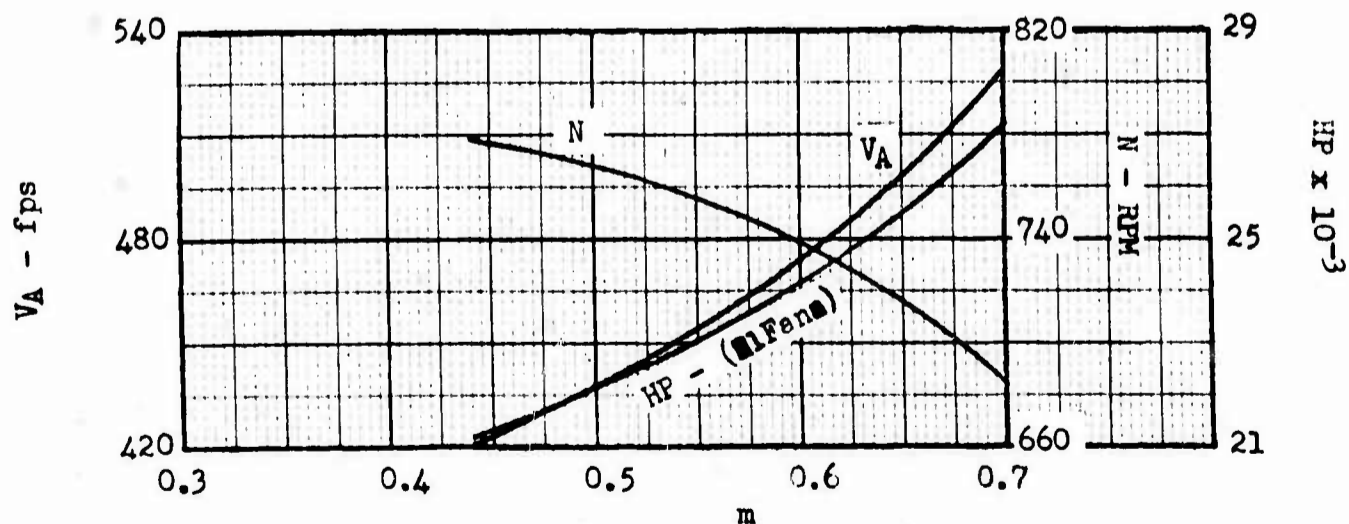
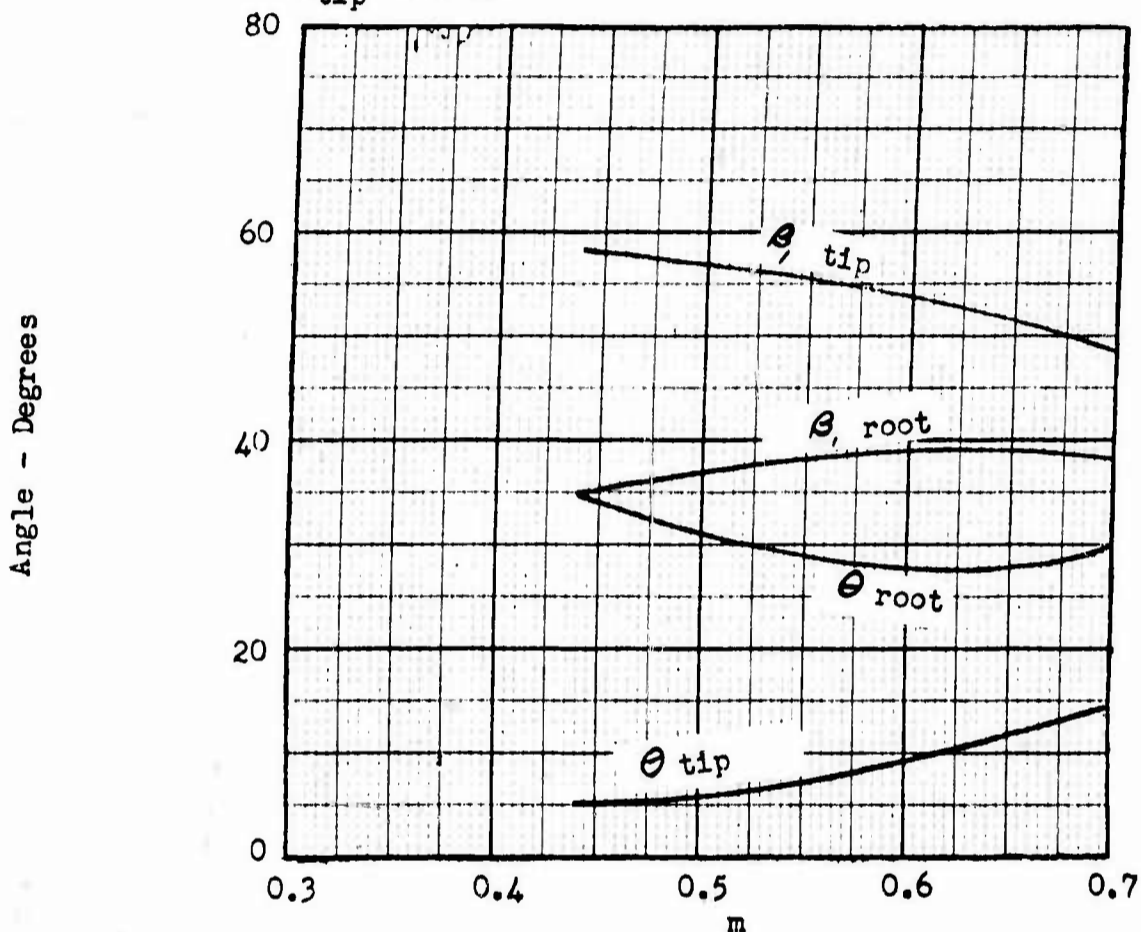


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FIGURE 9

VARIATION OF FAN DESIGN
PARAMETERS WITH ANNULUS RATIO

$A_E/A_F = 1.0$ $W_{1tip} = 800 \text{ fps}$
 $T = 56,000 \text{ #/fan}$ $\rho = 0.00178 \text{ slugs/ft}^3$
 $R_{tip} = 8.35'$



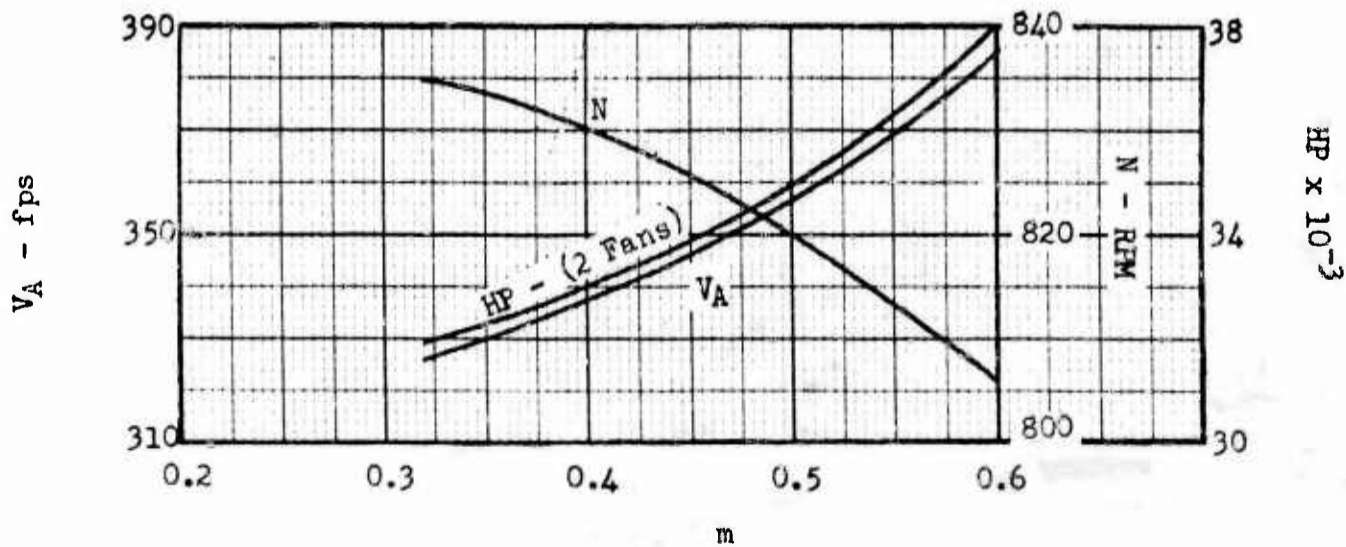
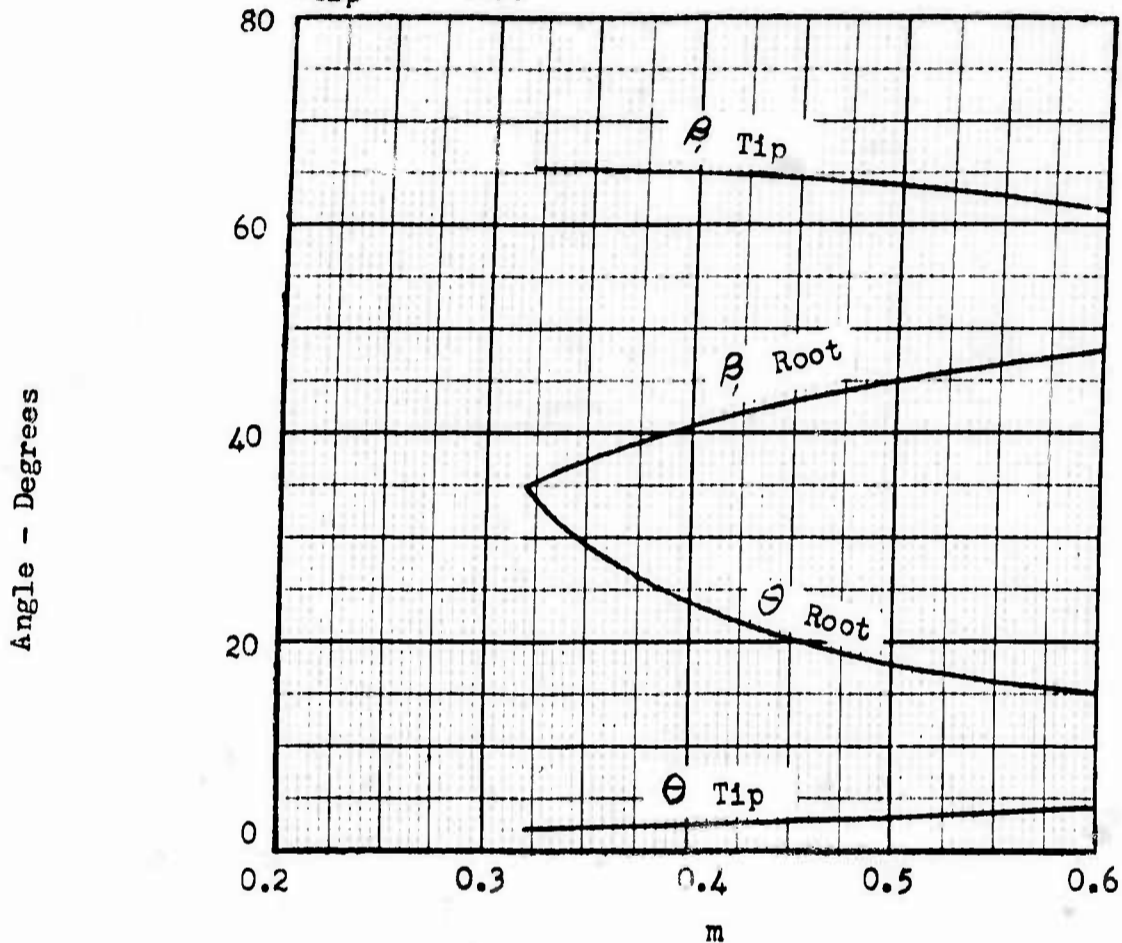
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FIGURE 10

VARIATION OF FAN DESIGN
PARAMETERS WITH ANNULUS RATIO

$A_E/A_F = 1.5$ $W_{tip} = 800 \text{ fps}$
 $T = 56,000 \text{ lb/fan}$ $\rho = 0.00178 \text{ slugs/ft}^3$
 $R_{tip} = 8.35'$



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FIGURE 11

VARIATION OF FAN DESIGN
PARAMETERS WITH ANNULUS RATIO

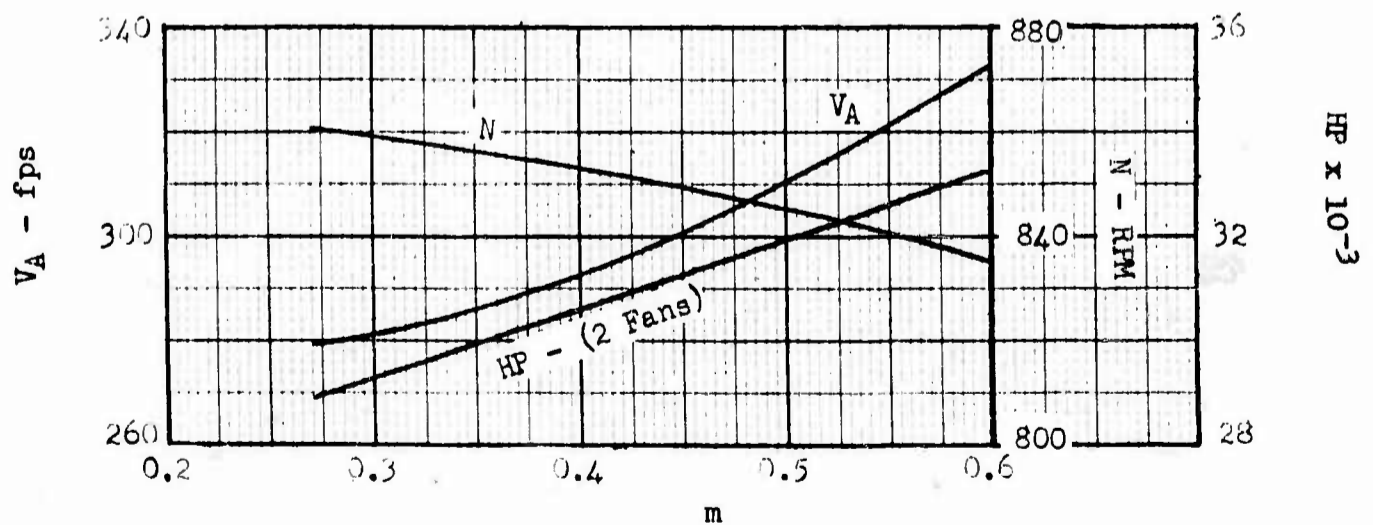
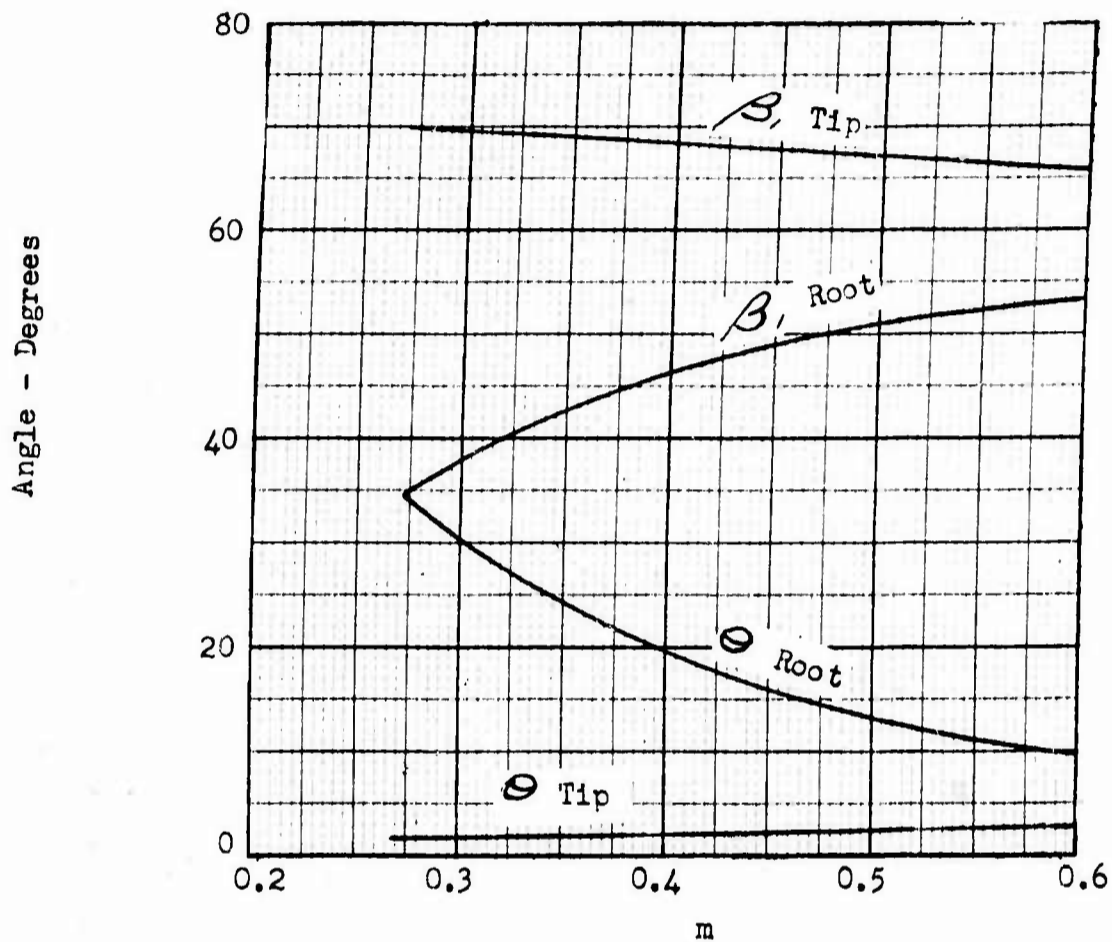
$$A_E/A_F = 2.0$$

$$T = 56,000 \text{ #/fan}$$

$$R_{tip} = 8.35'$$

$$W_{l_{tip}} = 800 \text{ fps}$$

$$\rho = 0.00178 \text{ slugs/ft}^3$$



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FIGURE 12

VARIATION OF FAN DESIGN
PARAMETERS WITH ANNULUS RATIO

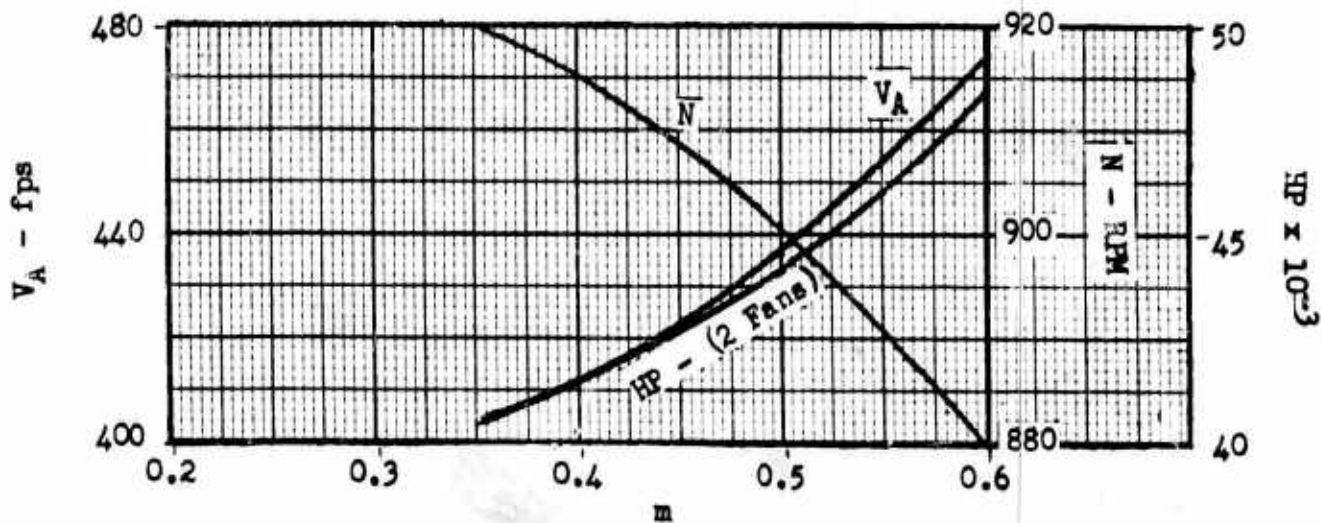
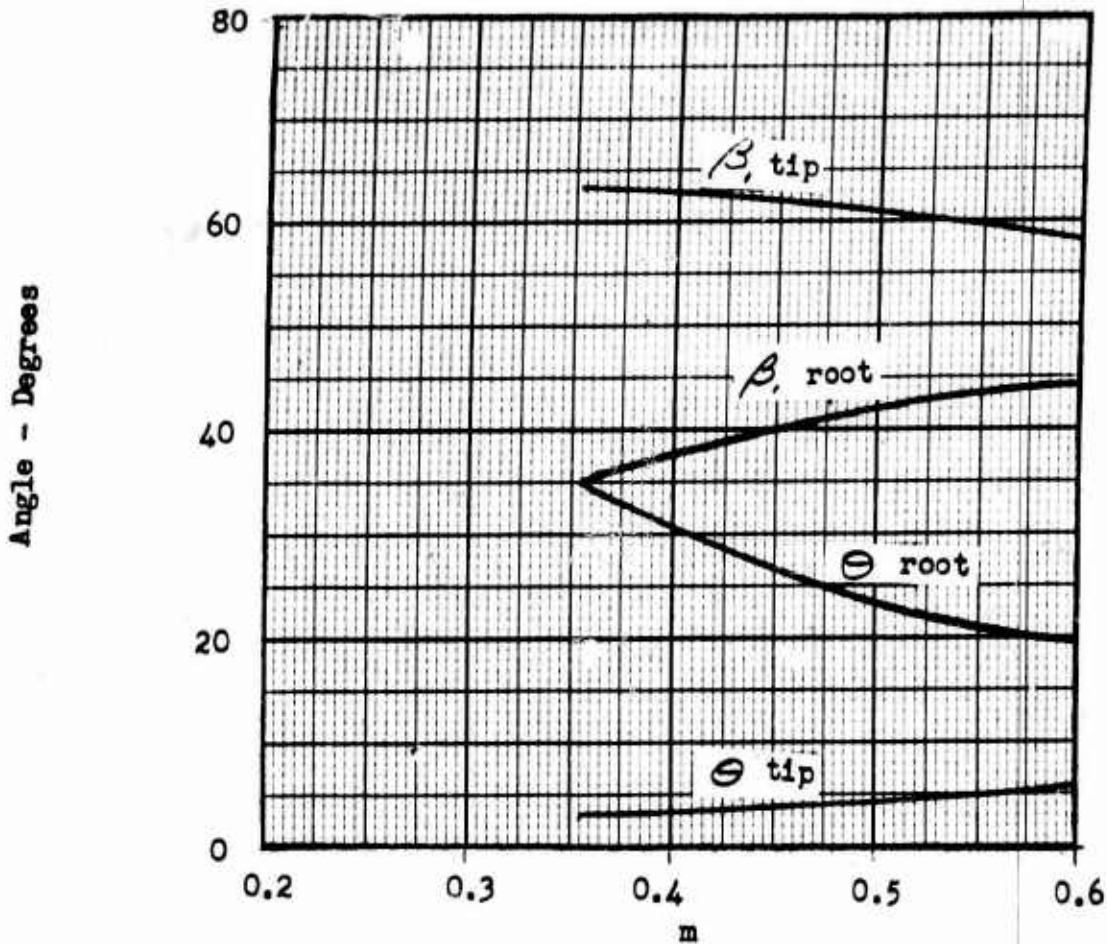
$$A_E/A_F = 1.0$$

$$\text{Thrust} = 56,000\#/fan$$

$$R_{tip} = 8.35'$$

$$W_{tip} = 900 \text{ fps}$$

$$\rho = 0.00178 \text{ slugs/ft}^3$$



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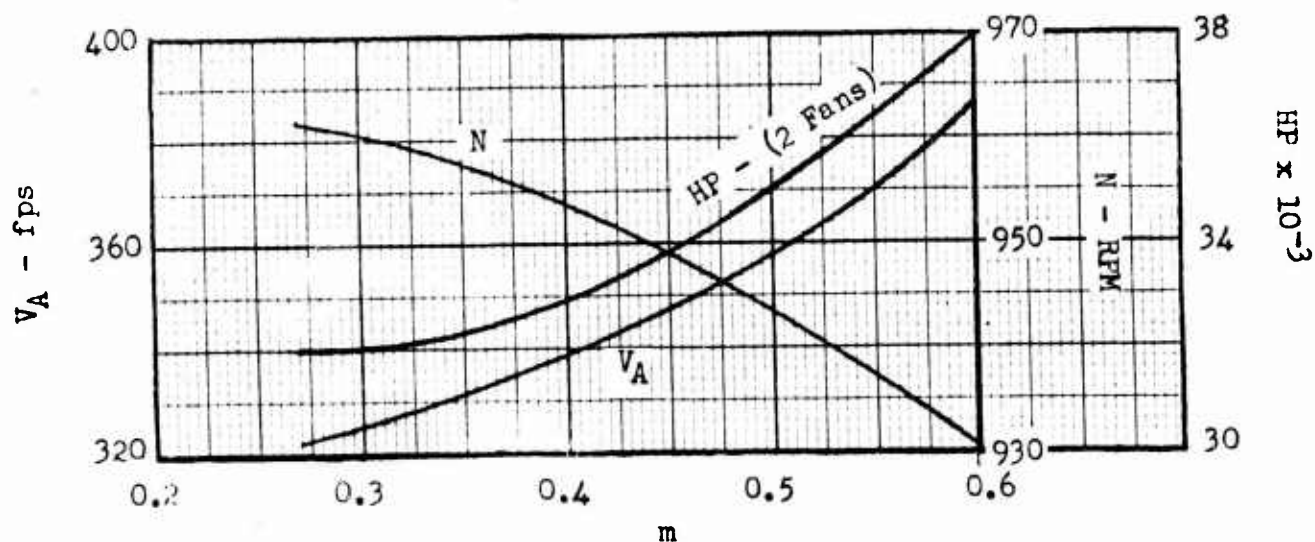
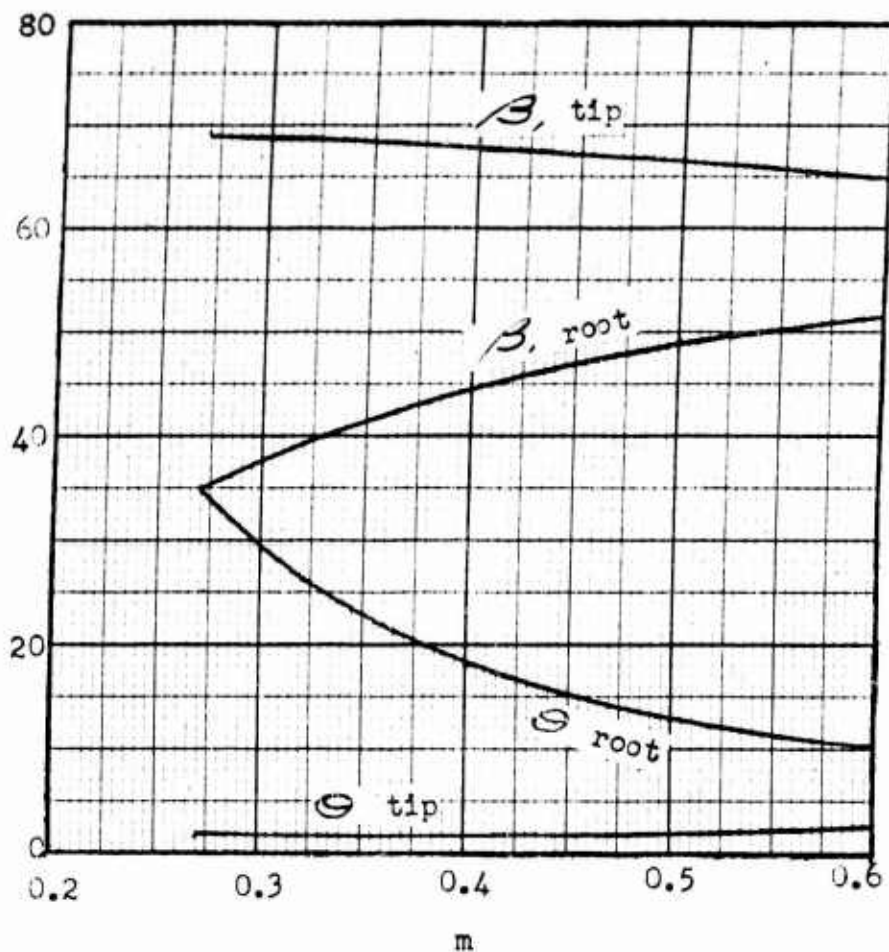
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FIGURE 13
VARIATION OF FAN DESIGN
PARAMETERS WITH ANNULUS RATIO

$A_E/A_F = 1.5$ $W_{tip} = 900 \text{ fps}$
 Thrust = 56,000#/fan $\rho = 0.00178 \text{ slugs/ft}^3$
 $R_{tip} = 8.35'$

Angle - Degrees



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FIGURE 14

VARIATION IN FAN DESIGN
PARAMETERS WITH ANNULUS RATIO

$$A_E/A_F = 2.0$$

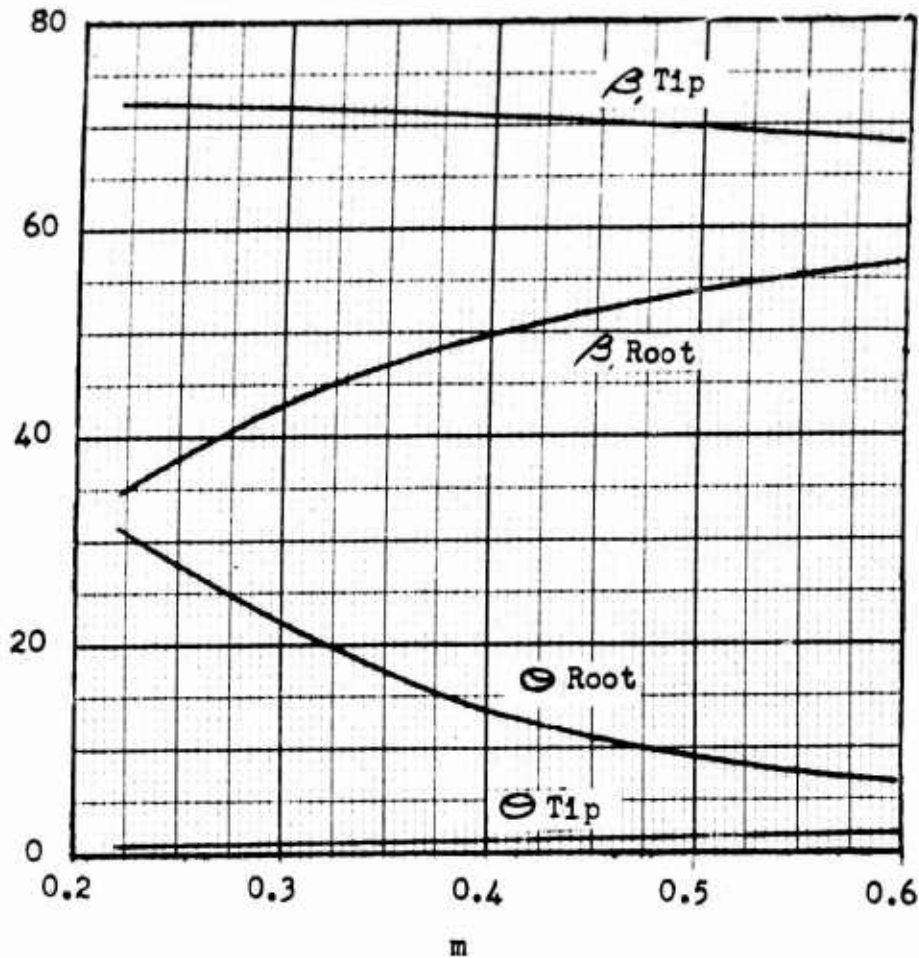
$$\text{Thrust} = 56,000 \text{ lb/fan}$$

$$R_{tip} = 8.35'$$

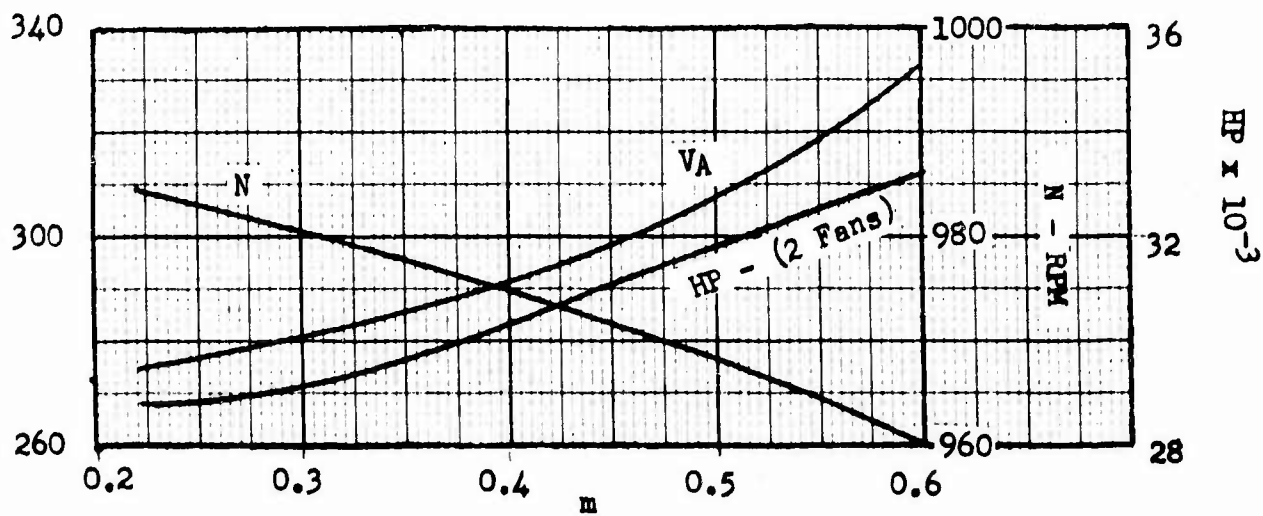
$$W_{tip} = 900 \text{ fps}$$

$$\rho = 0.00178 \text{ slugs/ft}^3$$

Angle - Degrees



V_A - fps



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FIGURE 15

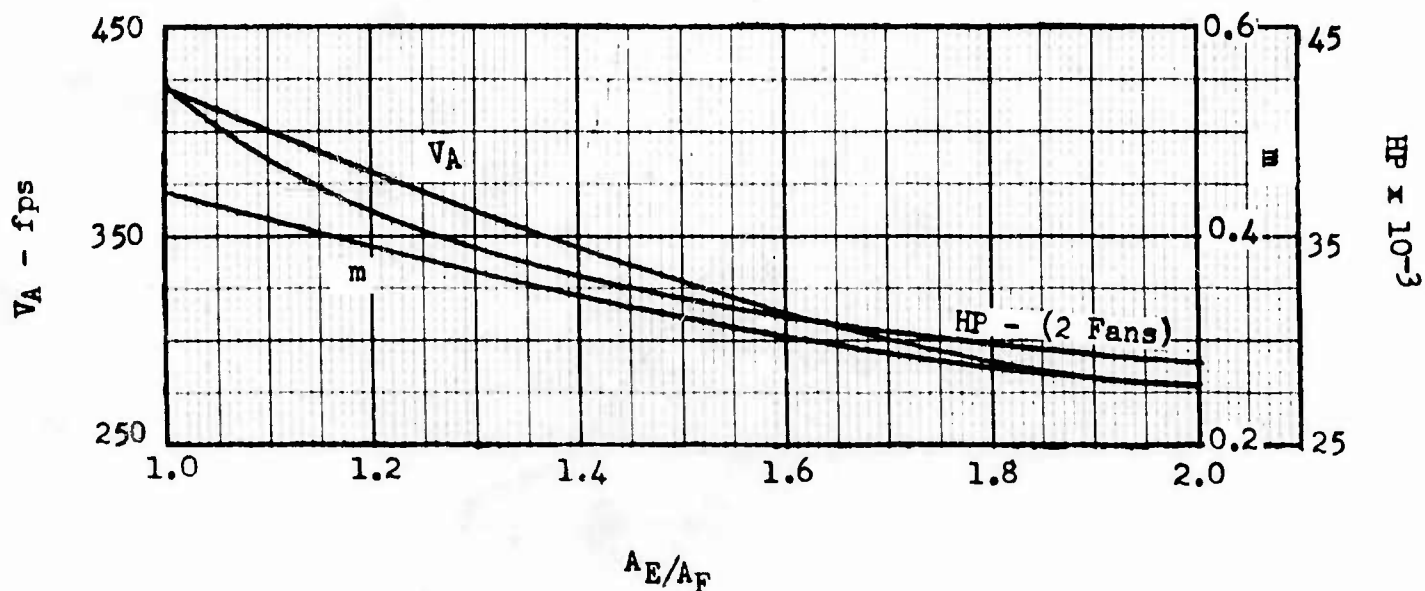
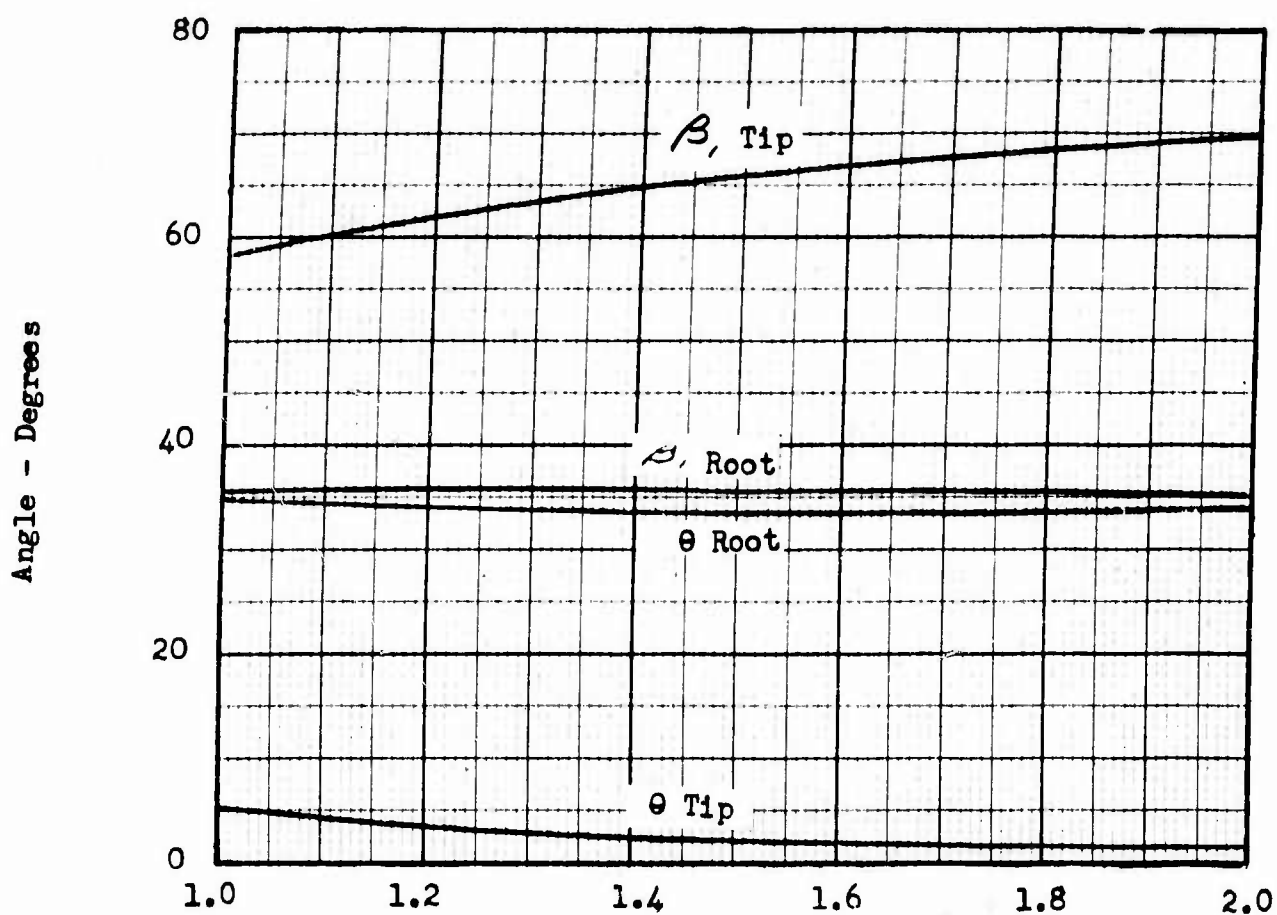
VARIATION IN FAN DESIGN PARAMETERS WITH
AREA RATIO AT MINIMUM ROOT RADIUS

$$T = 56,000 \text{#/fan}$$

$$W_{\text{tip}} = 800 \text{ fps}$$

$$R_{\text{tip}} = 8.35'$$

$$\rho = 0.00178 \text{ slugs/ft}^3$$



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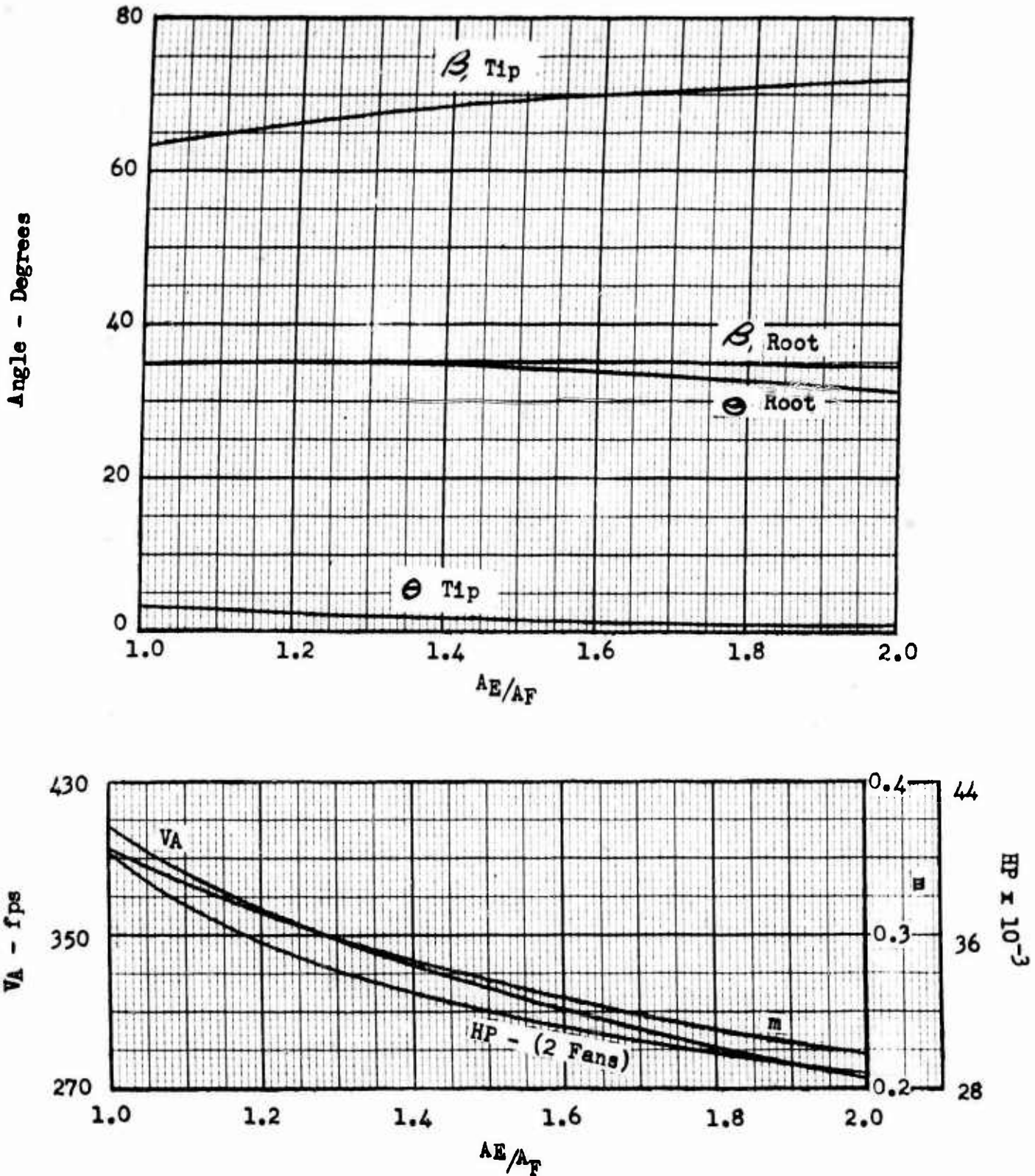
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FIGURE 16

VARIATION IN FAN DESIGN PARAMETERS WITH
DIFFUSION RATIO AT MINIMUM ROOT RADIUS

Thrust = 56,000#/fan
 $R_{tip} = 8.35'$

$W_{tip} = 900$ fps
 $\rho = 0.00178$ slugs/ft³

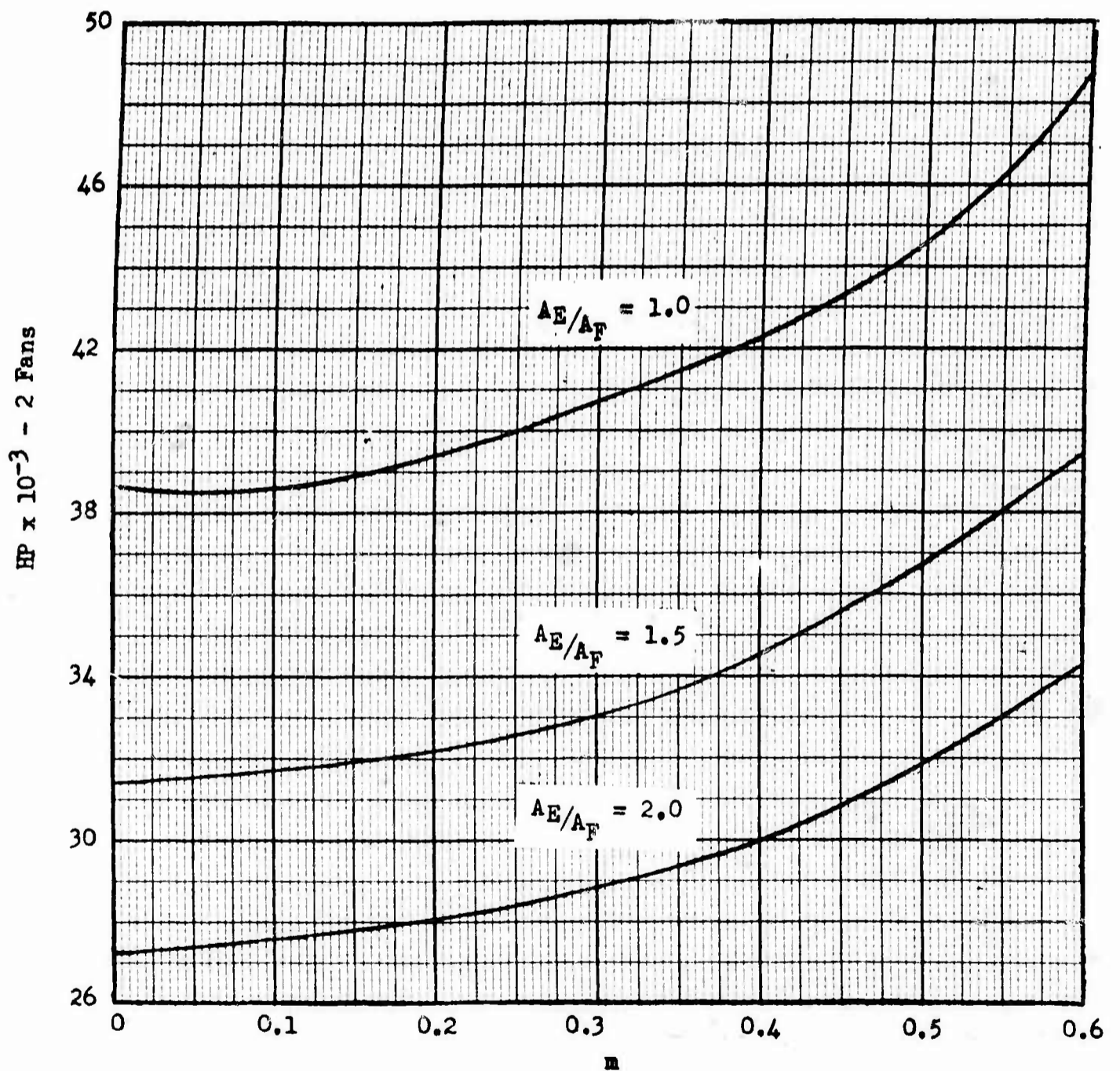


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FIGURE 17
HORSEPOWER VS ANNULUS RATIO FOR
INDICATED DIFFUSION RATIOS

$T = 56,000\#/fan$
 $R_{tip} = 8.35'$

$\rho = 0.00178 \text{ slugs/ft}^3$



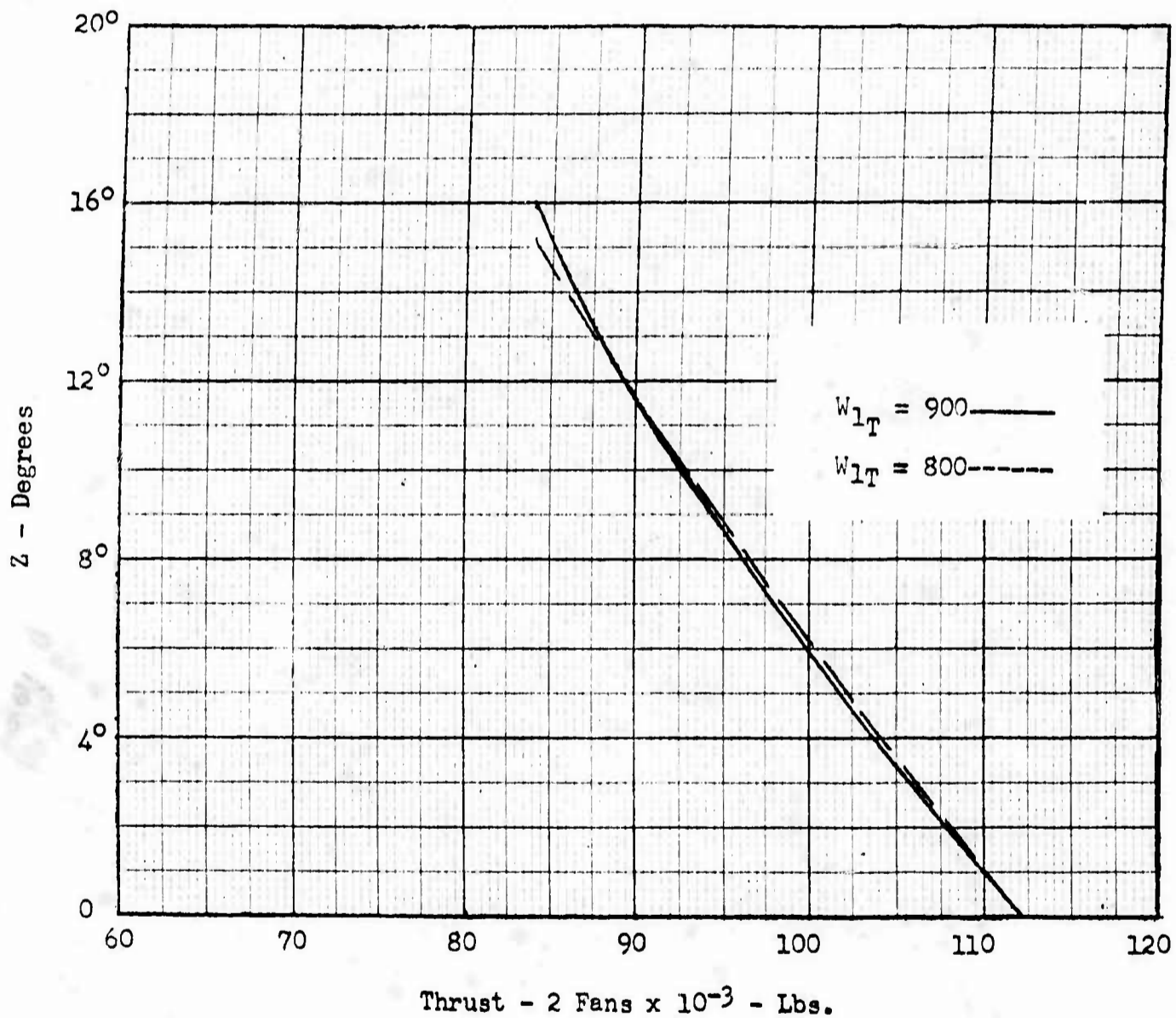
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FIGURE 18
INLET GUIDE VANE TURNING ANGLE VS THRUST FOR
NON-DIFFUSED DUCT AT MINIMUM ROOT RADIUS

$$R_{tip} = 8.35'$$

$$\rho = 0.00178 \text{ slugs/ft}^3$$



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